Progress in the Application of Landform Analysis in Studies of Semiarid Erosion

GEOLOGICAL SURVEY
CIRCULAR 437

Progress in the Application of Landform Analysis in Studies of Semiarid Erosion

By S. A. Schumm and R. F. Hadley

GEOLOGICAL SURVEY CIRCULAR 437

Washington 1961

United States Department of the Interior
STEWART L. UDALL, *Secretary*

Geological Survey
William T. Pecora, *Director*

First printing 1961
Second printing 1967

Free on application to the U.S. Geological Survey, Washington, D.C. 20242

CONTENTS

ILLUSTRATIONS

Progress in the Application of Landform Analysis in Studies of Semiarid Erosion[1]

By S. A. Schumm and R. F. Hadley

ABSTRACT

The analysis of topographic and hydrologic data gathered during studies of erosion in semiarid areas of Western United States show the following relation: (a) Mean annual sediment yield from small drainage basins is related to a ratio of basin relief to length; (b) mean annual runoff from small drainage basins is related to drainage density; (c) mean annual sediment yield per unit area decreases with increase in drainage area; (d) the form of some convex hill slopes is related to surficial creep; (e) asymmetry of drainage basins, including differences in hill-slope erosion and drainage density, is related to microclimatic variations on slopes of diverse exposure; (f) the cutting of discontinuous gullies is closely related to steepening by deposition of the semiarid valley floor; (g) aggradation in ephemeral streams seems to be most prevalent in reaches where the ratio of contributing drainage area to channel length is relatively small; and (h) stream-channel shape, expressed as a width-depth ratio, is related to the percentage of silt-clay in bed and bank alluvium.

The above relations cannot be detected without measurement of terrain characteristics. They further indicate the importance of quantitative terrain analysis in studies of erosion.

INTRODUCTION

The impetus given to quantitative geomorphology by Strahler (1957) has led to several recent publications on the techniques of landform analysis. This report reviews the results obtained by applying some of these techniques to studies of the geomorphic and hydrologic characteristics of small drainage basins on the semiarid public lands of Western United States. These studies by the authors are part of the soil and moisture program of the Department of the Interior carried out by the Geological Survey.

This brief review of work completed and in progress demonstrates some relations among topographic and hydrologic characteristics of small drainage basins. There is no attempt in this report to offer detailed physical explanations for the existence of the relations presented. Such explanations are attempted in the reports listed as references; the purpose here is simply to indicate the application of quantitative landform analysis to studies dealing with the hydrology and erosional characteristics of semiarid drainage basins.

Landform analysis may range from field measurements of gross drainage-basin characteristics to the preparation and analysis of detailed topographic maps. Generally, the work reported herein was of a reconnaissance nature because of the lack of good topographic maps and aerial photographs for the areas investigated. Therefore, landform analysis may be little more than the surveying of a hill-slope profile; however, measurement rather than qualitative description characterized the approach.

Comparisons of sediment yields, from small drainage basins in diverse climatic regions, show that mean annual rates of erosion are greatest in semiarid regions, excluding the effects of cultivation on highly erosive soils in some humid regions. Maximum sediment yields, in areas where the mean temperature is about 50°F, occur where the annual precipitation is between 10 and 15 inches (Langbein and Schumm, 1958). Sediment yields decrease sharply on both sides of this maximum, owing in one instance to a deficiency of runoff and in the other to increased density of vegetation. Average precipitation in the areas discussed here is less than 20 inches, and density of vegetation is low, generally less than 30 percent. These studies, therefore, were made in areas of high sediment yield. Such areas are ideal for the study of erosive processes and

[1]Presented at American Association for the Advancement of Science Symposium on Quantitative terrain studies, Chicago, Ill., Dec. 27, 1959.

the effects of landforms and erosion on each other.

Although rates of sediment yield are generally high in semiarid regions, the annual rates are variable. Consequently, it is necessary to collect records for long periods to obtain a dependable relation between the hydrologic and geomorphic characteristics of a drainage basin. However, if records longer than 5 years were required, little hydrologic data would be available for most semiarid regions. Therefore, 5 years of hydrologic record was accepted as the minimum required for correlation with basin charateristics.

The work to be described was grouped into two sections. The first includes small drainage basins that were studied as units, that is, the general topographic characteristics of the drainage basin were related to the hydrologic characteristics. In the second section only components of the drainage basin were considered, that is, hill slopes and selected reaches of stream channels.

THE DRAINAGE BASIN AS A UNIT

RELATIVE RELIEF AND SEDIMENT YIELD

Mean annual sediment yield was calculated from measurements of sediment deposited in stock-water reservoirs in Wyoming, Colorado, Utah, New Mexico, and Arizona. The 59 drainage basins studied ranged in size from 0.1 to 18.2 square miles. The relative relief of these drainage basins is expressed as a relief ratio, which is the relief of the drainage basin divided by basin length measured in a straight line approximately parallel to the major drainage channel. Basin relief was measured from the spillway elevation of the reservoir to the maximum elevation on the divide. However, in basins where isolated high points on the divide tend to give undue weight to basin height, relief was measured to an average divide elevation. It is felt that this modification is justified because isolated high points commonly have a small area and have little effect on rates of sediment yield. Relief ratio has been related to other drainage-basin characteristics, for example, channel gradient and mean maximum slope angles (Schumm, 1956a).

The mean annual sediment yields from the 59 drainage basins were averaged by rock type and plotted against the relief ratio in figure 1. As shown on this figure, the points for drainage areas underlain by sandstone and conglomerate plot close to the lower end of the regression line as both relative relief and sediment yields are low. The shale areas are characterized by greater relative relief and higher sediment yields; the seemingly anomalous high relative relief in some shale areas may be attributed to recent gullying and badland development. The relation between sediment yield and relief ratio for 14 small drainage basins, underlain by rocks of the Fort Union formation and located in the Cheyenne River basin of eastern Wyoming, is shown on figure 2 (Hadley and Schumm, 1961).

Studies in Texas by Maner (1958) have shown a correlation between relief ratio and sediment yield. Recently in Illinois no meaningful correlation was found owing perhaps to the effects of cultivation within the drainage basins (Stall and Bartelli, 1959).

More refined drainage-basin parameters can be used where topographic maps are available. For areas where there are none or only aerial photographs of poor quality, simple measures such as relief ratio are readily obtained. Basin length can be measured on the poorest aerial photograph, and relief can be obtained readily with an altimeter in the field.

Figures 1 and 2 indicate that with uniform climate, sediment yield from small drainage basins depends on geomorphic characteristics. The good correlation between mean annual sediment yield and relief ratio suggests that a practical approach to an erosion classification of semiarid lands may be through a quantitative analysis of the geomorphic characteristics of a region.

DRAINAGE DENSITY AND MEAN ANNUAL RUNOFF

Another important hydrologic variable is mean annual runoff. Runoff data were obtained by measuring inflow of water to small reservoirs in the Cheyenne River basin from April through October, 1951–54 (Culler, 1961). In spite of the short record a correlation exists (fig. 3) when drainage density, the total length of channels per square mile of drainage area, is plotted against mean annual runoff for 13 small drainage basins ranging in size from 0.1 to 3.0 square miles (Hadley and Schumm, 1961). The relation shown in this figure

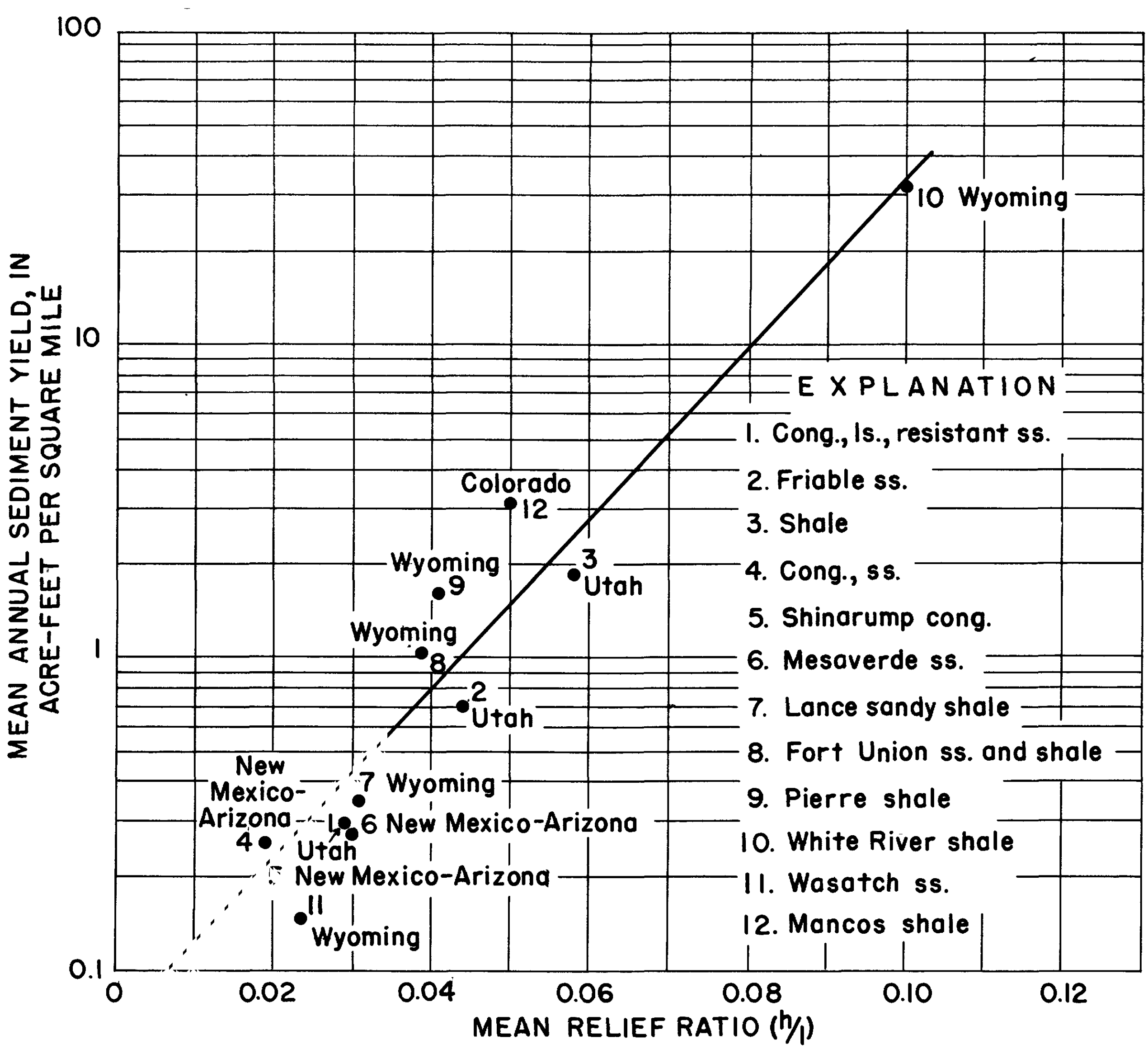

Figure 1.—Relation of mean annual sediment yield to mean relief ratio for 59 small drainage basins in Wyoming, Colorado, Utah, New Mexico, and Arizona.

suggests that drainage density, if not dependent simply on runoff, is at least dependent on the same variables that influence runoff. The importance of this relation to the hydrologist is that annual discharge may be predicted for ungaged drainage basins when the geomorphic characteristics are expressed in quantitative terms.

DRAINAGE AREA AND SEDIMENT YIELD

The decrease in unit rate of sediment yield with increasing size of drainage basin has been noted in many studies of sediment yield (Glymph, 1954; Hadley and Schumm, 1961). The relation between sediment yield and size of contributing drainage area for 73 small drainage basins in the Cheyenne River basin shows such a decrease (fig. 4). The gentler stream gradients and slope angles near the mouth of a drainage basin, when compared with the generally more rugged topography near drainage divides, may explain the decrease in sediment yield with increased drainage area. In addition, water losses in sandy ephemeral-stream channels (Schumm and Hadley, 1957) may promote deposition and hinder sediment movement out of the larger drainage basins. One other factor may be important; that is,

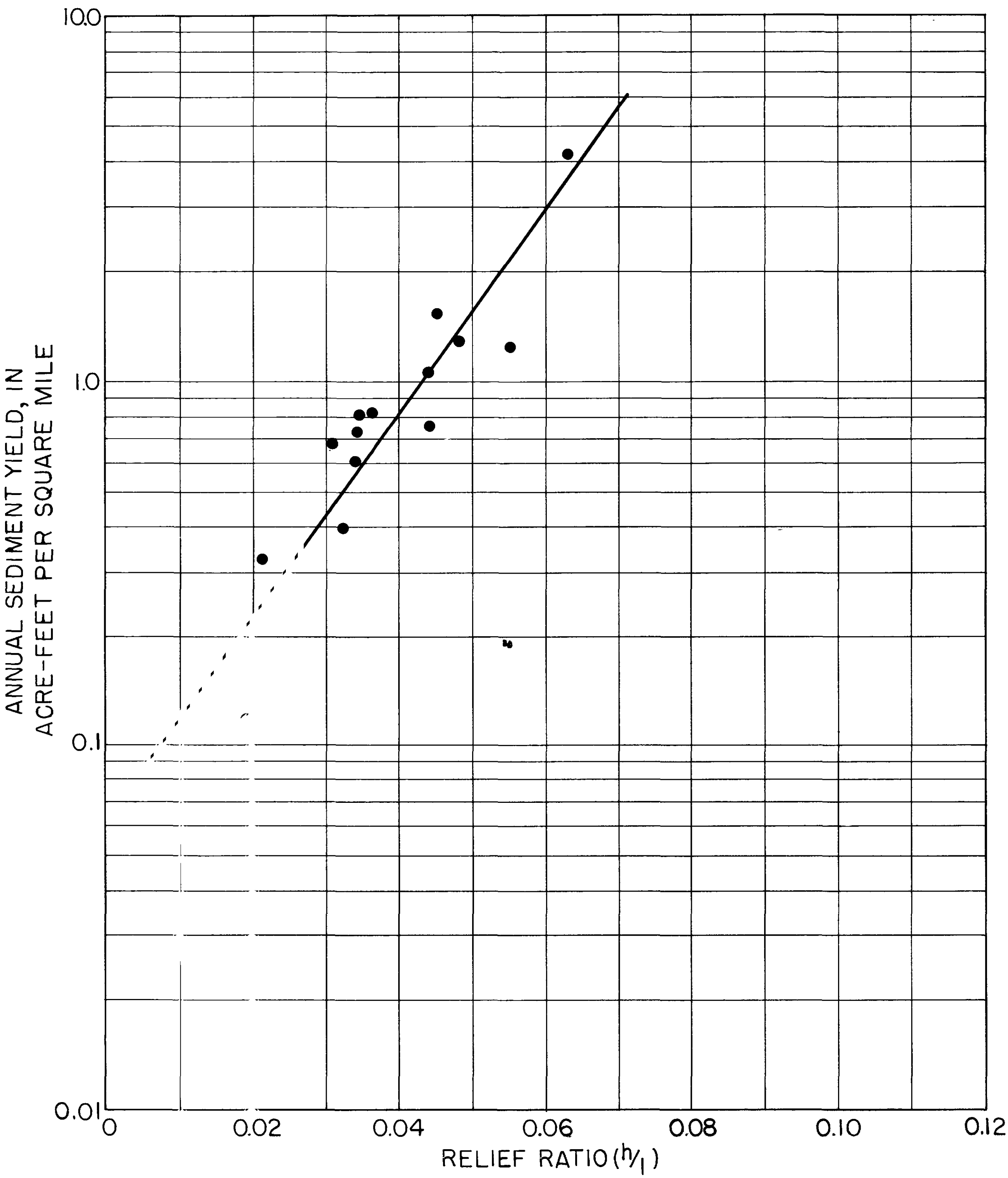

Figure 2.—Relation of mean annual sediment yield to relief ratio for 14 small drainage basins underlain by the Fort Union formation in eastern Wyoming.

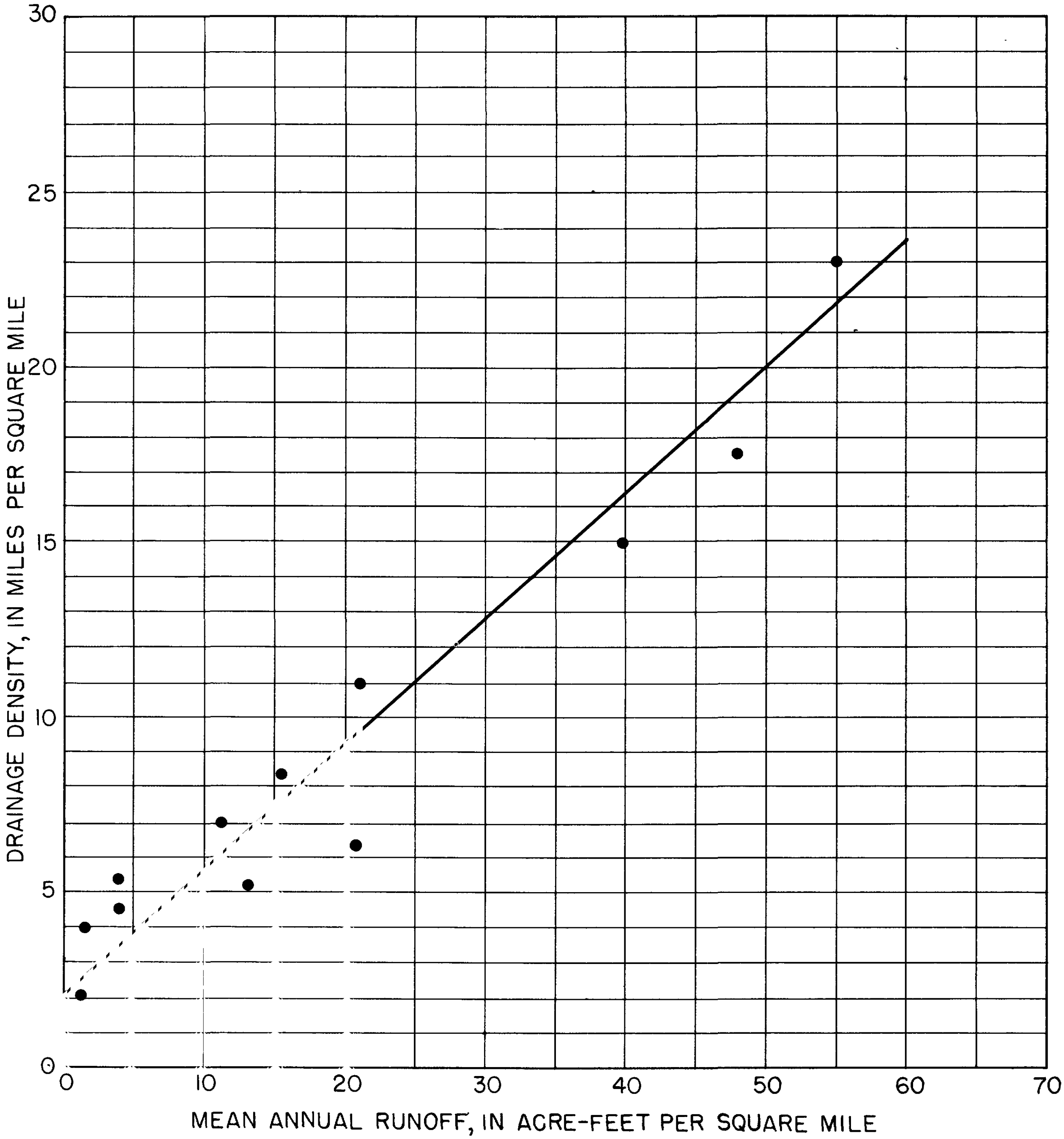

Figure 3.—Relation of mean annual runoff to drainage density for 13 small drainage basins in eastern Wyoming.

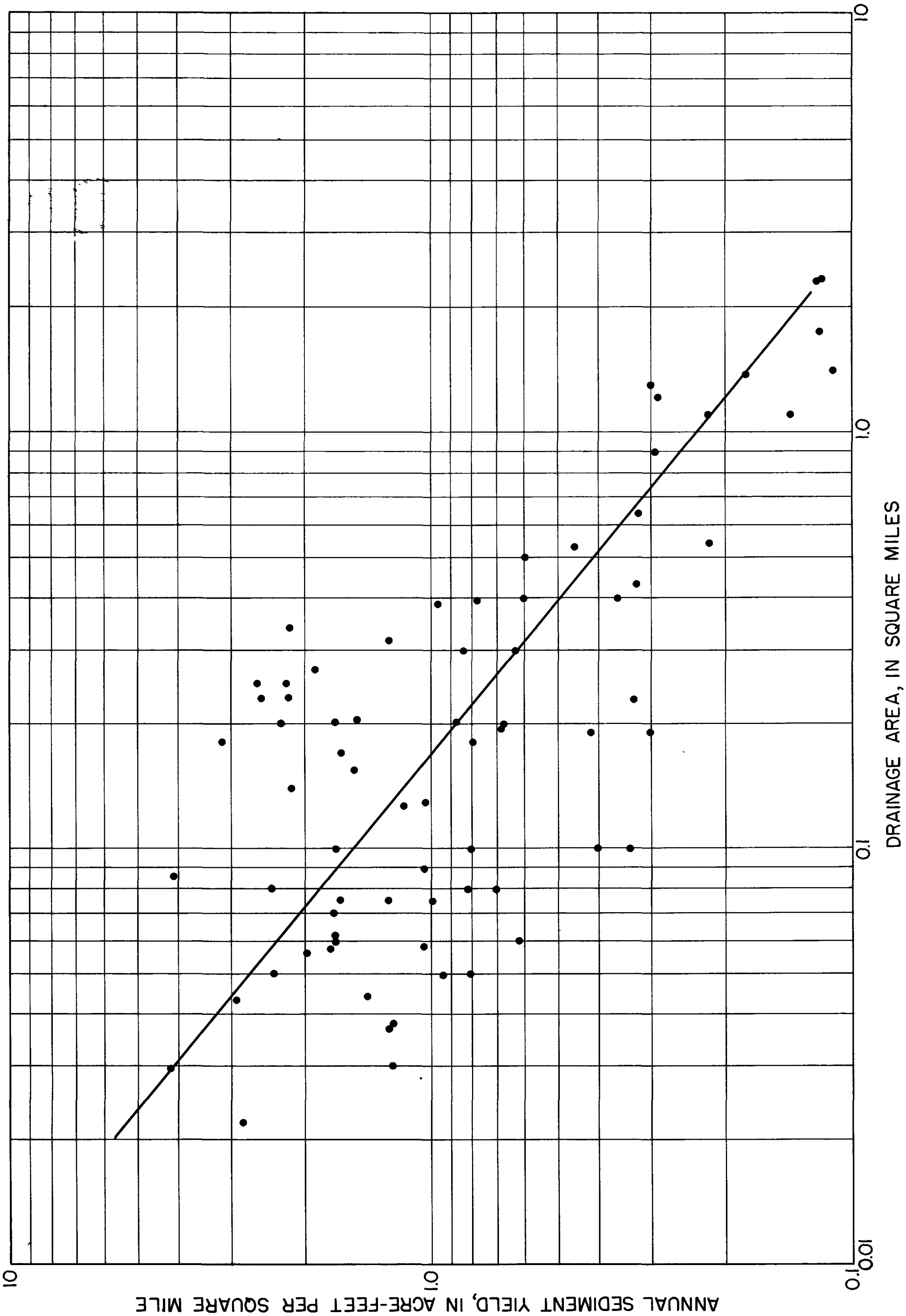

Figure 4. —Relation of mean annual sediment yield to drainage area for 73 small drainage basins in eastern Wyoming.

the formation of bottomlands or flood plains bordering the stream channel.

To determine the relation between bottomland formation and drainage area, data from 76 small drainage basins in the Cheyenne River basin were used. The area of bottomland in each drainage basin was measured from aerial photographs. Bottomland begins to form in drainage basins larger than 0.1 square mile. The ratio of the area of bottomland to upland reaches a maximum in basins of about 2.5 square miles and remains nearly uniform for all larger basins. In the drainage basins with areas larger than 0.1 square mile, the increase in area of bottomland with increased drainage area will hinder sediment movement from hill slopes to the adjacent stream channels and will afford sites for sediment deposition during floods, thereby decreasing sediment yields.

DRAINAGE-BASIN COMPONENTS

In addition to relief ratio, which is a parameter characteristic of the drainage basin as a unit, many components of a drainage basin, when expressed quantitatively, can be related to erosion processes or to variables influencing erosion rates and processes. For example, the inclination and aspect of hill slopes markedly affect the rates and mechanics of runoff and erosion. Therefore, it is desirable to attempt to relate such characteristics of drainage-basin components to the existing data concerning erosion processes.

HILL SLOPES

FORM

Investigations of hill-slope erosion by the Soil Conservation Service have shown that both slope length and slope inclination are important factors determining erosion rates on a hill slope (Smith and Wischmeier, 1957); further, the shape of a hill slope may be related to the dominant erosive process operative on the slope (Schumm, 1956b). For example, in Western United States many straight steep slopes, which retreat at a constant inclination, form under the action of rainwash. Convex slopes, on the other hand, apparently form under the action of creep, owing to alternate swelling and compaction of lithosols high in montmorillonite. The recognition of this process through its effect on slope-profile form may be important with regard to attempts to improve grazing conditions over large areas of Western United States, for on slopes where such swelling and creeping of the surficial material occurs only the most hardy range plants grow. Perhaps the degree of curvature of a hill-slope profile may indicate the relative importance of rainwash or creep.

An additional example of the dependence of hill slope form on erosional processes has been reported by Hadley and Rolfe (1955). Many hill slopes in eastern Wyoming and western South Dakota and Nebraska are broken by erosional scarplets less than 2 feet high (fig. 5). These features are roughly parallel to adjacent stream channels and in some cases follow a slope nearly on contour for as much as a quarter of a mile. The scarplets are developed in a surficial mantle of relatively high permeability which overlies a fine-grained less permeable weathered shale. Flow of water along the contact between the mantle and underlying weathered shale causes a basal sapping of the scarplet and subsequent migration upslope. The scarplets are termed seepage steps after the process which is responsible for their maintanence. The initial seepage step is probably the result of channel cutting in the valley floor.

ASPECT

Within any one area microclimatic variations dependent on the direction of slope exposure or aspect affect hill-slope and drainage-basin development. Studies now being made by Hadley show that hill slopes of different aspect have marked contrasts in morphology, hydrology, and vegetal cover. These contrasts have been observed and reported from several localities and may be common at all latitudes. North-facing slopes in semiarid regions of Western United States are steeper, less dissected, and support a more luxurious growth of vegetation than slopes in the same drainage basin facing southward, which are often deeply rilled and nearly barren.

Six small drainage basins were selected for an intensive study of the effects of slope aspect. Between 30 and 50 measurements of slope inclination were made in each of the

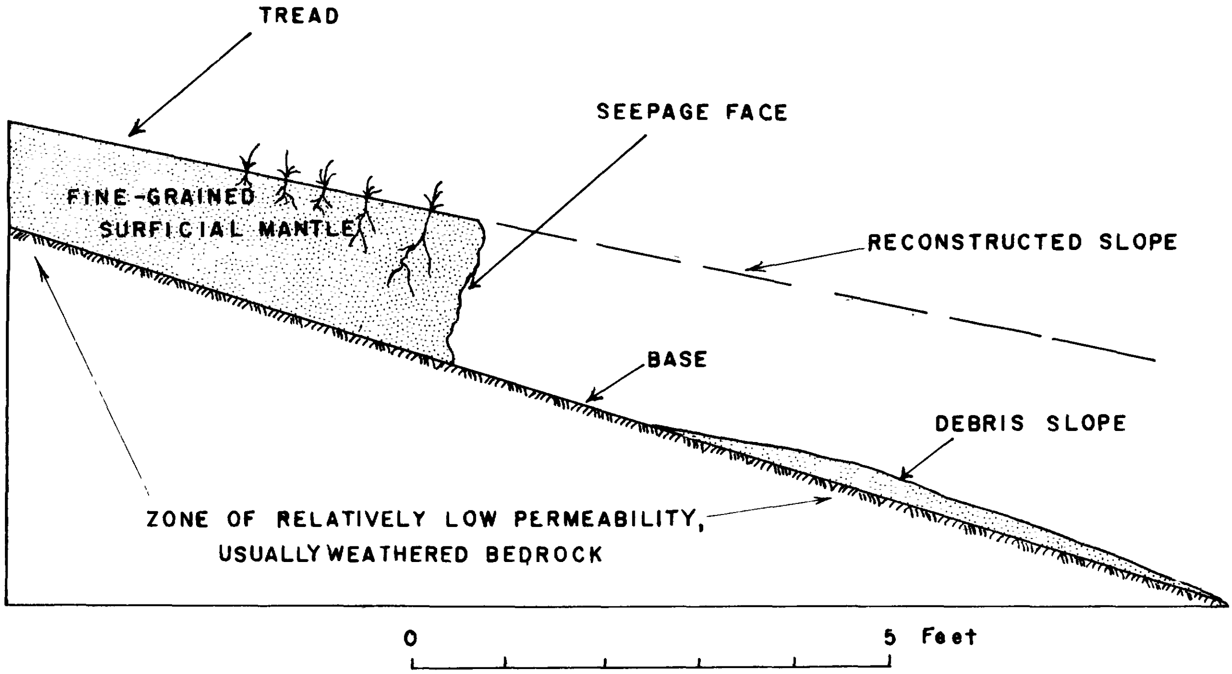

Figure 5.—Diagram of typical seepage step showing integral parts.

six basins, on slopes facing nearly every compass direction. When the data from one of the basins are plotted on polar coordinate paper (fig. 6), the steepest slopes are found to be facing north and northeast. This is because the smaller amount of solar radiation received on these slopes tends to inhibit the loss of soil moisture, resulting in additional moisture which in turn supports more vegetation capable of retarding erosion. In contrast, the south-facing slopes lose soil moisture rapidly with consequent poorer vegetative cover and more erosion.

Measurements of drainage density show that the number of channels on the south-facing or northern side of a drainage basin is more than twice that found on the southern side of the drainage basin (fig. 7). The average drainage density, as measured in the study areas, is 11.3 miles per square mile on the northern side and only 5.2 miles per square mile on the southern side of the drainage basins.

Because of these differences in hill-slope erosion there is a tendency for the main stream channel in an east-west-trending drainage system to be shifted to the south by the eroded material derived from the south-facing slopes. This channel migration has caused asymmetrical development of drainage basins in several widely separated localities of dissimilar geology and climate. An index of symmetry is used to describe the effects of channel shifting on basin shape. The index is the ratio of the distances from the main drainage channel to the northern and to the southern drainage divide. An index of 1.0 describes a symmetrical drainage basin. Each of the basins selected for study (fig. 7) has an index greater than 1.0 indicating an asymmetry caused by shifting of the main drainage channel to the south.

STREAM CHANNELS

DISCONTINUOUS GULLIES

An important problem in semiarid areas is the downcutting of ephemeral-stream channels to form gullies. In many semiarid valleys downcutting is not continuous throughout the valley, but instead trenched reaches are separated by uncut reaches of the valley floor. Trenched reaches are known as discontinuous gullies. The formation of continuous and discontinuous gullies may be attributed to climate change or overgrazing, but whatever the ultimate cause of the trenching, until the mechanics of aggradation and degradation are known, little can be attempted in the way of conservation measures aimed at the prevention of gully cutting. Surveys (Schumm and

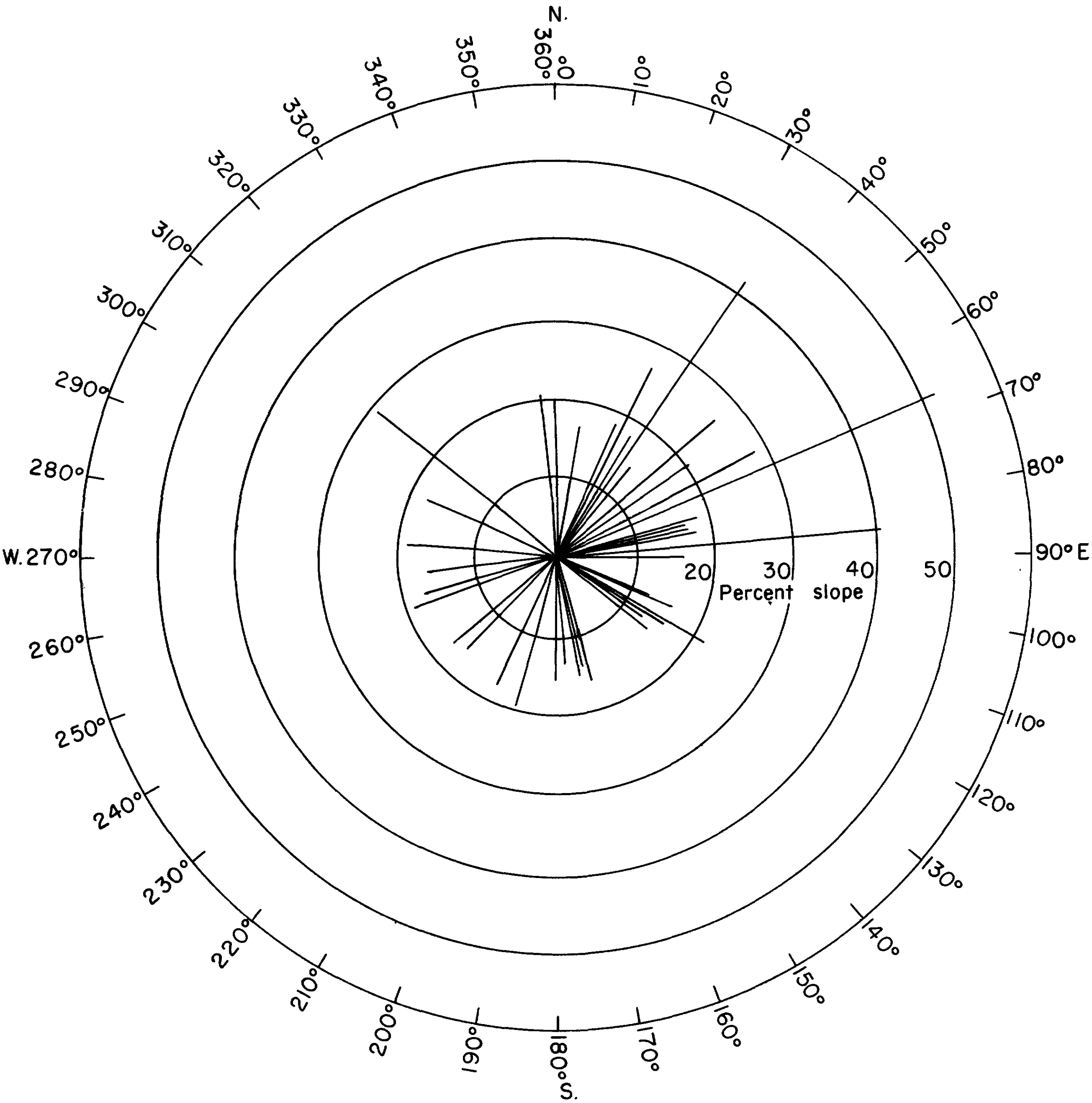

Figure 6.—Rose diagram showing relation of slope aspect and steepness of slope.

Hadley, 1957) of the longitudinal profiles of channels in Wyoming and New Mexico indicated that the points of initial trenching could be identified.

The trenching of the alluvial fill in each of the valleys surveyed was associated with a steepening of the gradient on the valley fill (fig. 8). The cutting seems mostly to have originated on these steeper reaches, and the channel has eroded up the valley with only minor extension of the trench down the valley. The larger valleys studied range in drainage area from 0.6 to 19 square miles; in these, cutting begins on slopes of from 1.5 to 2.5 percent. The smaller valleys range in drainage area from 0.05 to 0.5 square mile; here the cutting begins on slopes of from 2.5 to 5.4 percent. The higher gradients required for trenching on smaller drainage basins suggests an inverse

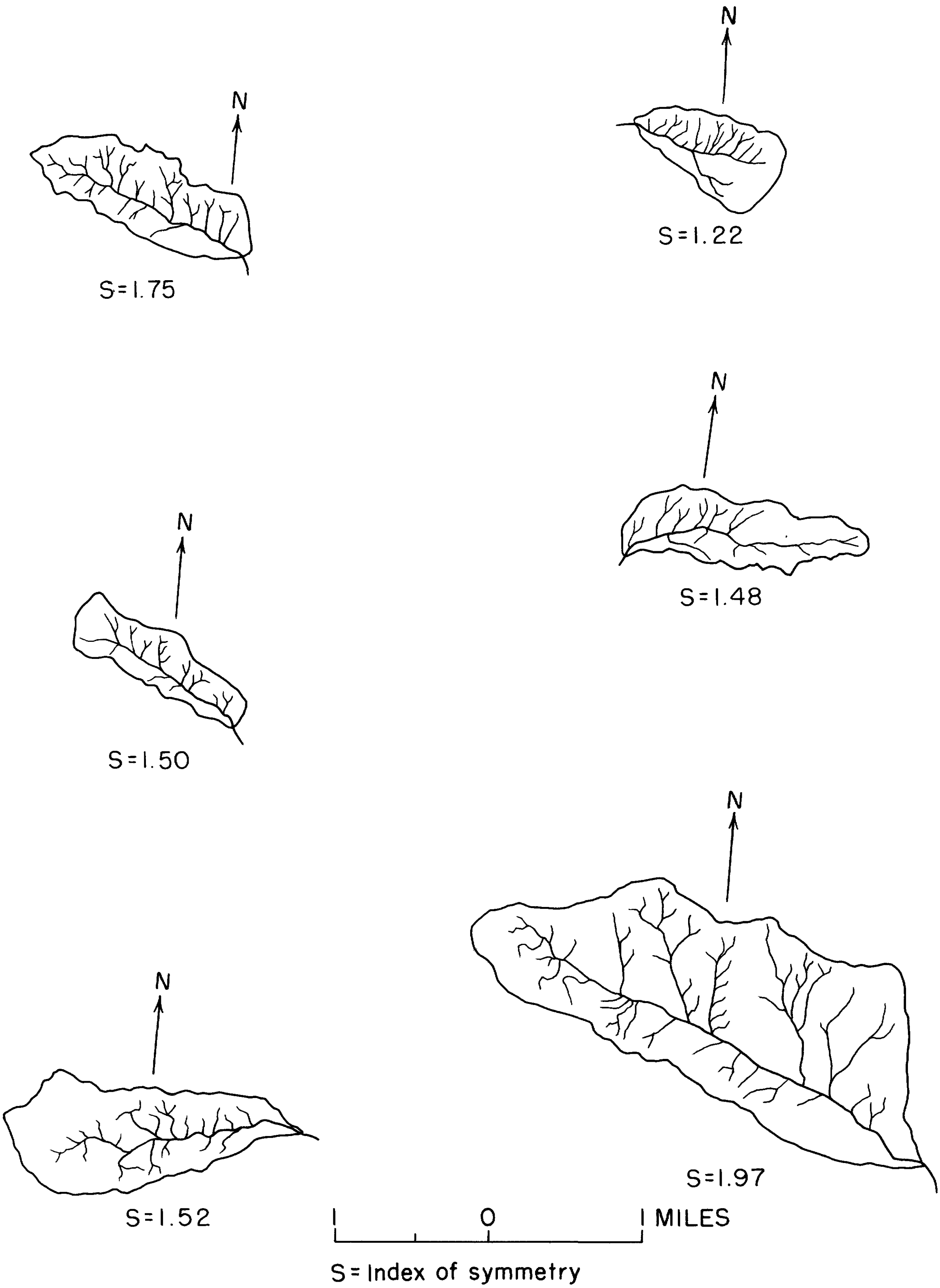

Figure 7.—Drainage nets of six selected basins in Niobrara County, Wyo., showing asymmetrical basin development and differences in drainage density owing to exposure.

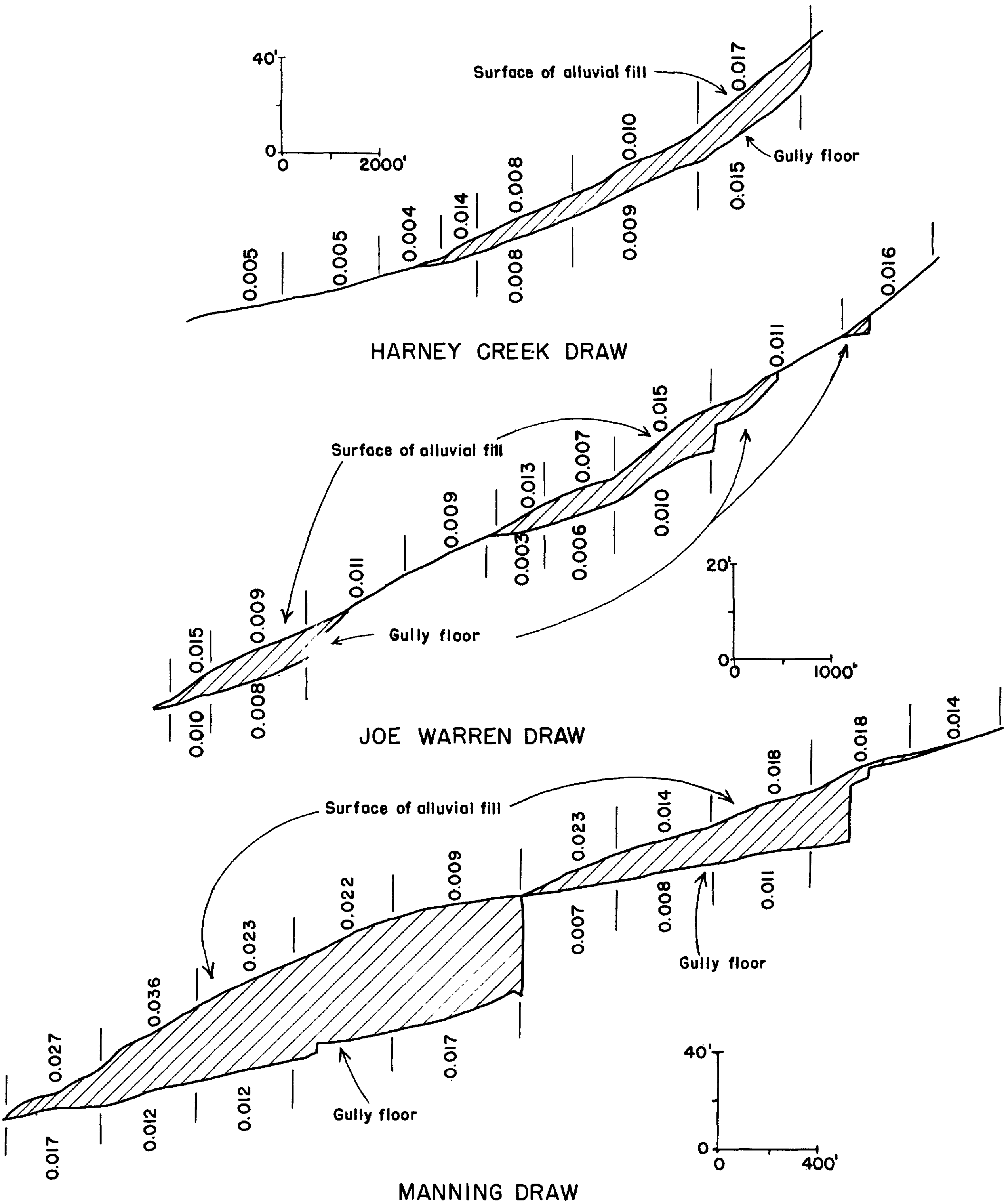

Figure 8.—Profiles of discontinuous gullies in Niobrara County, Wyo. Figures are gradient for each section of the profile in feet per foot.

relation between discharge and the angle at which the fill will be trenched; that is, for a given storm, discharge will be less from the small drainage systems and cutting will not occur on a slope as gentle as in a neighboring larger basin with greater discharge.

The foregoing indicates that knowledge of the geomorphic characteristics of ephemeral streams is necessary to an understanding of their past, present, or future activity. Also, geomorphic factors may possibly be predominant in determining when a valley will be trenched. That is, before change of climate or increased grazing can cause the trenching of a valley, sufficiently steep reaches of the channel or valley floor must have formed.

AGGRADATION

Trenching of stream channels in semiarid regions may begin on critical reaches of the channel, which can be identified by measurements of the valley profile. It may also be possible to identify the reaches of a stream most susceptible to aggradation by measurements of stream profiles. The reaches of a channel in which aggradation is most likely to occur are located where few tributaries enter; that is, in a reach of the channel in which the increment of contributing drainage area to the increment of channel length is relatively small (Schumm, 1961, in press). The reason for the aggradation is probably the loss of water by infiltration into the channel bed, which results in an increased sediment concentration in the remaining flow. Therefore, aggradation may occur in those reaches of the channel where little water is added to the existing flow.

Data presented in the accompanying table show the increase in drainage area with channel length along four aggrading streams. The ratio of these two values are given for both aggrading and stable reaches of the channels studied, and aggradation occurs consistently in a reach along which the increase of drainage area per mile of channel length is significantly less than that for the stable channel reaches. For example, in the Sage Creek area there is an average increase of 2 square miles of drainage area for each mile of channel length along the stable reach; whereas, this decreases to only 0.2 square mile per mile of channel length along the aggrading reach.

Ratio of drainage area to channel length

Study area	Nonaggrading reach (section numbers)	Aggrading reach (section numbers)	Drainage area (square miles)	Channel length (miles)	Area-length ratio
Sage Creek, S. Dak.	1–6	....	12.7	5.7	2.2
		6–7	.26	1.1	.2
Sand Creek, Nebr...	2–6	....	6.4	3.6	1.8
		6–10	1.7	1.6	1.1
Arroyo de los Frijoles and Arroyo Calabasas, N. Mex.	C–6	....	19.4	3.2	6.0
		6–9	[1]7.2	2.7	2.7
Bayou Gulch, Colo..	1–4	....	9.0	1.1	8.1
		4–5	.5	.2	2.5

[1]Adjusted for noncontributing area.

This suggests that if aggradation were to be induced in a stream channel as a conservation measure, the site of the structure should be selected at least partly on the basis of changes in the ratio of drainage area to channel length along the channel.

CHANNEL SHAPE

During the progress of the aggradation studies just mentioned, a great contrast in the characteristics of stream channels formed of either predominantly sandy or silty matetials was observed. The more sandy the channel the wider and shallower it appeared. Data on stream-channel dimensions and the size distribution of sediment forming the perimeter of the channel were collected at 70 locations at which the channels were considered stable (Schumm, 1960). Channel shape expressed as a width-depth ratio is plotted against the weighted mean percent silt-clay forming the banks and bed of the channel (fig. 9). Silt-clay is defined as that sediment passing the 200-mesh sieve, or smaller than 0.074 mm. The weighted mean was calculated to give the bed and bank sediments a weight proportional to the length of channel perimeter composed of each type of material. The correlation shown in figure 9 reveals that as the bed and bank materials contain progressively more silt-clay, the channels become relatively narrower and deeper. This is attributed to the greater cohesion and resistance to erosion of alluvium containing high percentages of silt-clay.

Discharge apparently has a minor effect on channel shape, for the data (fig. 9) were obtained from channels characterized by a great range of mean annual discharge—from about 20 to 4,920 cfs. The drainage area above the

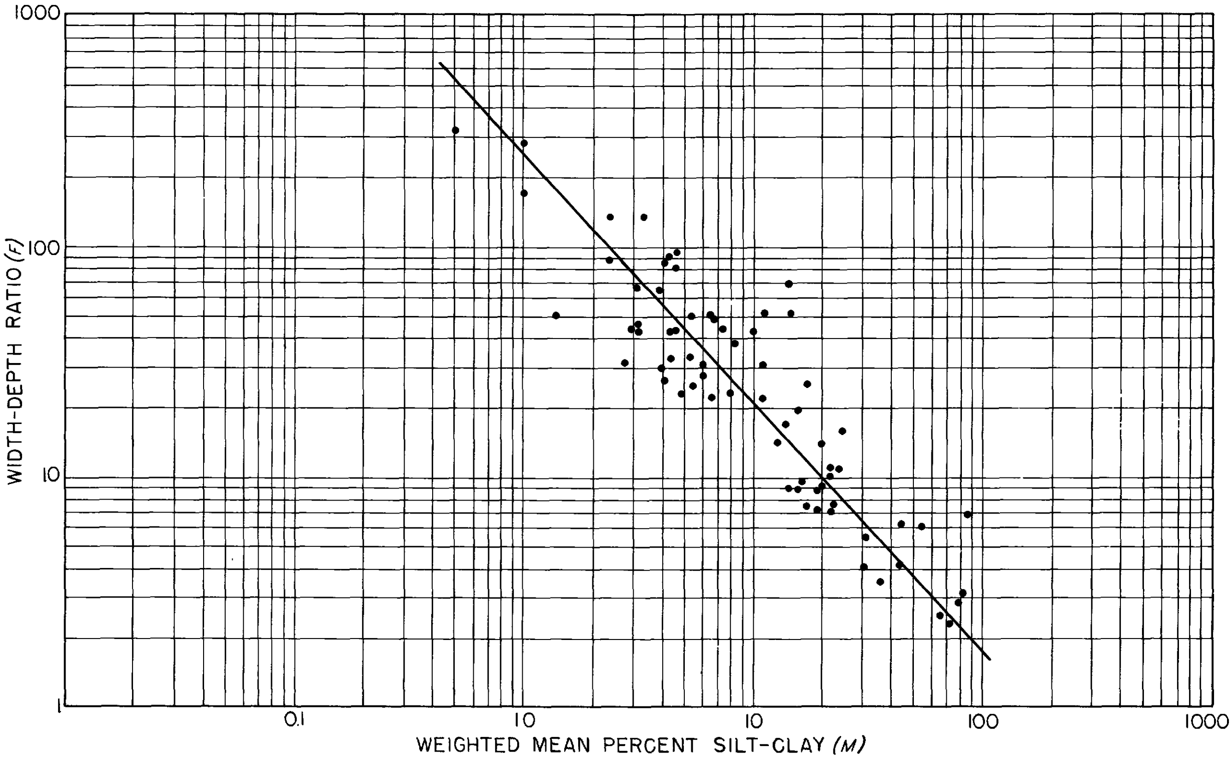

Figure 9.—Relation of width-depth ratios to weighted mean percent silt-clay in alluvium of bed and banks at 70 channel cross sections.

cross sections sampled ranges from 1.7 square miles for the smallest ephemeral stream to 56,700 square miles for the Kansas River at Topeka, Kans.

Data collected along individual streams show that changes in channel width and depth in a downstream direction, that cannot be attributed to changes in discharge, are related to downstream variations in the percent silt-clay in the stream channel. In addition, the introduction of sediment from tributaries into the main channel may cause a change in the shape of the main channel. Stream-channel shape, therefore, depends largely on variations of the silt-clay content of channel banks and bed. The importance of this relation to other aspects of fluvial morphology and hydraulics has yet to be investigated.

REFERENCES

Culler, R. C., 1961, Hydrology of stock-water reservoirs in upper Cheyenne River basin: U. S. Geol. Survey Water-Supply Paper 1531-A.

Glymph, L. M., Jr., 1954, Studies of sediment yields from watersheds: Association internationale d Hydrologie Publication (Assembleé générale de Rome), v. 1, p. 178–191.

Hadley, R. F., and Rolfe, B. N., 1955, Development and significance of seepage steps in slope erosion: Am. Geophys. Union Trans., v. 36, p. 792–804.

Hadley, R. F., and Schumm, S. A., 1961, Sediment sources and drainage-basin characteristics in upper Cheyenne River basin: U. S. Geol. Survey Water-Supply Paper 1531-B.

Langbein, W. B., and Schumm, S. A., 1958, Yield of sediment in relation to mean annual precipitation: Am. Geophys. Union Trans., v. 39, p. 1076–1084.

Maner, S. B., 1958, Factors affecting sediment delivery rates in the Red Hills physiographic area: Am. Geophys. Union Trans., v. 39, p. 669–675.

Schumm, S. A., 1956a, Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey: Geol. Soc. Am. Bull., v. 67, p. 597–646.

———1956b, The role of creep and rainwash on the retreat of badland slopes: Am. Jour. Sci., v. 254, p. 693–706.

———1960, The shape of alluvial channels in relation to sediment type: U.S. Geol. Survey Prof. Paper 352-B, p. 17–30.

Schumm, S. A., 1961, The effect of sediment characteristics on erosion and deposition in ephemeral-stream channels: U.S. Geol. Survey Prof. Paper 352-C, in press.

Schumm, S. A., and Hadley, R. F., 1957, Arroyos and the semiarid cycle of erosion: Am. Jour. Sci., v. 255, p. 161–174.

Smith, D. D., and Wischmeier, W. H., 1957, Factors affecting sheet and rill erosion: Am Geophys. Union Trans., v. 38, p. 889–896.

Stall, J. B., and Bartelli, L. J., 1959, Correlation of reservoir sedimentation and watershed factors, Springfield Plain, Illinois: Illinois State Water Survey Rept. Inv. 37, 21 p.

Strahler, A. N., 1957, Quantitative analysis of watershed geomorphology: Am. Geophys. Union Trans., v. 38, p. 913–920.

INT.DUP.,D.C.61-90509

☆ U.S. GOVERNMENT PRINTING OFFICE · 1967 O—274-526